OSSE Spectral Analysis Techniques

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ABSTRACT

Analysis of spectra from the Oriented Scintillation Spectrometer Experiment (OSSE) is complicated because of the typically low signal-to-noise ($\sim 0.1\%$) and the large background variability. The OSSE instrument was designed to address these difficulties by periodically offset-pointing the detectors from the source to perform background measurements. These background measurements are used to estimate the background during each of the source observations. The resulting background-subtracted spectra can then be accumulated and fitted for spectral lines and/or continua. Data selection based on various environmental parameters can be performed at several stages during the analysis procedure. In order to achieve the instrument's statistical sensitivity, however, it will be necessary for investigators to develop a detailed understanding of the instrument operation, data collection, and the background spectrum and its variability. A brief description of the major steps in the OSSE spectral analysis process will be described, including a discussion of the OSSE background spectrum and examples of several observation strategies.

INTRODUCTION

The OSSE instrument consists of four separate, nearly identical detectors. The primary detecting element of each detector is a large area NaI(Tl)-CsI(Na) phoswich crystal providing primary gamma-ray spectral capabilities over the energy range $0.05 - 10.0$ MeV and secondary gamma-ray and neutron spectral capabilities at energies above 10 MeV. Passive tungsten collimators provide a field-of-view which is $3.8^\circ \times 11.4^\circ$ (FWHM), with the long direction of the collimators oriented parallel to the spacecraft Y-axis. Each detector has a separate elevation control system which provides independent positioning of the detectors about an axis parallel to the spacecraft Y-axis. During source observations, periodic background measurements are performed by offset-pointing the detectors from the source. Source and background measurements are typically alternated at two minute intervals, with backgrounds being sampled on each side of the source position along the instrument scan plane.

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Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **1991**	2. REPORT TYPE	3. DATES COVERED **00-00-1991 to 00-00-1991**

4. TITLE AND SUBTITLE **OSSE Spectral Analysis Techniques**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Research Laboratory,4555 Overlook Avenue, SW,Washington,DC,20375**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**		**13**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

The primary data from the OSSE instrument consists of time-averaged energy loss spectra from the individual phoswich detectors. The time interval for these accumulations is in the range 4 – 32 seconds, depending on the operating mode of the instrument. After accumulation, these spectra are inserted into the spacecraft telemetry stream. As a part of the ground processing of the telemetry data, the OSSE spectra are summed into detector pointing intervals (typically two minutes) and stored in Spectrum Database (SDB) files. The SDB files are the primary medium for storage of all OSSE spectral data and related housekeeping and environmental information. These files typically contain: 1) an SDB header containing detailed information about the instrument configuration and environmental conditions during the spectral accumulation (e.g. detector position, temperature, geomagnetic cutoff rigidity, time since last SAA passage, data quality, etc.), 2) the spectral data and uncertainties, 3) PHA channel energies and widths, 4) calibration information (e.g. pulse-shape discrimination efficiencies), and 5) additional auxiliary information, as required. The spectra from each detector are accumulated and stored separately. A typical two-week observation of a single source consists of $\sim$ 20,000 spectra, requiring $\sim$ 40 MBytes of storage. A more detailed description of the OSSE data products can be found in Strickman *et al.* (1991). A detailed description of the OSSE instrument and its operation can be found in Johnson *et al.* (1989) and Cameron *et al.* (1992).

ANALYSIS SYSTEM

The primary OSSE data analysis system is the Interactive GRO/OSSE Reduction Environment (IGORE). The IGORE system was developed to provide an interactive scientific data analysis system for the reduction of OSSE data. The foundation of IGORE is the commercially available software package IDL (Interactive Data Language), which provides an interactive, programmable data manipulation language and application interface. Important additions to the native IDL capabilities include a simple interface mechanism for dynamically linking user written FORTRAN applications into the IGORE system and the support of IGORE structures which have been designed to minimize virtual memory requirements by allocating memory only as needed. IGORE also provides numerous applications to perform standard spectral analysis tasks. These applications are currently VAX/VMS FORTRAN specific and provide: 1) I/O access to OSSE data files, 2) access to OSSE Monte Carlo results and instrument response, and 3) the ability to move data between IGORE structures and local IDL variables. The IGORE system and applications were designed to retain the "look and feel" of IDL by providing similar command formats, interactive and batch programming capabilities, the ability to save/restore the analysis environment and associated data, and the option of journaling the user's analysis session. A more detailed description of the IGORE analysis system can be found in Grabelsky *et al.* (1991) and Strickman *et al.* (1991).

The primary method for manipulation of OSSE spectral data in IGORE is through an IGORE structure called a Spectral Data Record (SDR). The information in the SDR parallels that in the SDB file (e.g. SDB header, spectral data, uncertainties, channel

energies, etc.). Because of the large amount of data which is typically required to perform spectral analysis, the SDR typically only contains a pointer to the data record in the associated SDB file; the data fields in the SDR are generally populated only as required during the analysis process. A brief outline of the major steps in the OSSE spectral analysis process is shown in Figure 5. These analysis tasks are all performed in IGORE and are designed to allow the user to analyze the data in an iterative fashion by returning to any of several earlier analysis steps and repeating the analysis with new parameters.

BACKGROUND SPECTRUM

Because OSSE samples the background by offset-pointing the detectors from the source, an understanding of the background spectrum and its variability is necessary to perform background estimation effectively. There are many sources of background line and continuum emission which effect space-borne gamma-ray detectors (see Dyer *et al.* 1980). An example of a typical OSSE background spectrum is shown in Figure 1. Numerous background lines and several continuum components are visible. Several aspects of the observed background spectrum, in particular the time variability of line and continuum components as it relates to OSSE background estimation, are discussed below. For a detailed description and identification of background features in space-based gamma-ray scintillation detectors see Kurfess *et al.* (1989) and Share *et al.* (1989).

The dominant source of background is induced radioactivity resulting from particle interactions in the detector and surrounding material. Both cosmic-ray particles and particles trapped in the Earth's magnetic field contribute to the induced radioactivity. The dominant source of background from trapped particles is the passage of the spacecraft through the South Atlantic Anomaly (SAA), which occurs during $\sim 6-7$ orbits each day. The effects of cosmic-ray and SAA backgrounds vary over different time scales, depending on the modulation of the particles themselves and on the half-life of the induced radioactive species.

An example of the observed background time variability for two continuum window rates and for the background 511 keV line rate is shown in Figure 2. Also shown in this figure is the variation in the local vertical geomagnetic cutoff rigidity. Variation in the continuum rate at low energies is dominated by SAA induced radioactivities, as seen in the $1-2$ MeV window rates. This is primarily due to the activation of ^{128}I in the phoswich crystal. The endpoint energy of the subsequent β-decay (half-life $\sim$ 25 minutes) is 2.1 MeV, producing a strong background continuum at lower energies. At energies above $\sim$ 2 MeV the relative amplitudes of the SAA and cosmic-ray induced components of the background continuum are similar, as seen in the $2-5$ MeV window rates. These rates show a strong correlation with the local vertical geomagnetic cutoff rigidity. A similar correlation is seen in the fitted background 511 keV line rates.

The Earth's atmosphere and the spacecraft itself are also sources of gamma-rays, con-

tributing to the background at energies above a few hundred keV because of the non-zero instrument response outside of the field-of-view at these energies. The offset-pointing method of background estimation may produce residual systematics at these energies because of the varying instrument response to the Earth's atmosphere during the source and background observations and because of the potential modulation of the spacecraft background due to the detector motion. The magnitudes of these effects have not yet been quantified.

OBSERVATION STRATEGIES

Before beginning to analyze OSSE spectral data, it is important to understand the positioning strategy which was used during the observation. The positioning strategy, which specifies the positioning of each detector separately, is defined by OSSE mission operations and uploaded into the instrument prior to the observation. The positioning strategy may consist of up to eight different observation positions for each detector.

An example of a simple OSSE pointing strategy is shown in Figure 3. In this example, background observations are located on each side of the source position and are separated from the source position by 4.5°. This offset angle corresponds to the position of the first minimum of the angular response in the scan direction. Figure 3 also lists a typical observation sequence for each of the OSSE detectors. For each detector the accumulations alternate between source observations and background measurements. To reduce possible systematic effects, the sequencing of the source and background accumulations are different for each detector.

When performing observations in source-confused regions, or to generate a scan map of a region, a more complex pointing strategy may be required. An example of such a scan, used for an observation of the Galactic center region, is shown in Figure 4. In this example there are multiple source positions to provide a scan map of the region. The background observations are located on each side of the source positions and are separated from the central source position by 10° to minimize the possible residual response to diffuse emission. Figure 4 also lists one of the detector observation sequences used for this observation. For each detector the accumulations still alternate between source observations and background measurements, with the source position cycling between the central source position and one of the four outer source positions. As in the simple strategy described above, the sequencing of the source and background accumulations are different for each detector to reduce possible systematic effects.

While the two examples of observation strategies described above vary significantly in apparent complexity, the data collected from both may be analyzed in very similar ways. Much more complicated observation strategies may be constructed which use more than four of the eight possible detector positioning entries; however, care should be taken when constructing such strategies to ensure that the resulting data are analyzable.

SPECTRAL ANALYSIS

The OSSE spectral analysis is based on the concept of an Analyzable Unit (AU). An AU consists of a single source spectrum and a set of background spectra from one or more of the background offset positions. An AU may consist of spectra from a single detector only. The specified background spectra are used to estimate the background during the source observation. The number of background spectra required depends on the complexity of the background estimation model. In the simplest case (see Figure 3) an AU might consist of a source spectrum and two background spectra, one accumulated before and the other after the source observation. The background estimation model in this case might merely be a linear interpolation in time between the two background spectra. Because the observations alternate between source and background measurements, the same background spectrum may be be used to estimate the background for more than one source observation.

The major steps required to analyze OSSE spectral data are shown in Figure 5. The entire analysis procedure is performed in IGORE and, in general, each step consists of only one or two IGORE commands. The first step consists of identifying the SDB files containing the data to be analyzed and determining the positioning strategy used for the observation. Initial data selection is then applied to these data. This selection is performed using the IDL WHERE function and is based on information stored in the SDB header associated with each spectrum. The initial selection criteria are generally constructed to exclude data having poor data quality (e.g. telemetry or positioning errors) or data accumulated during times in which the source was occulted by the Earth. Additional data selection criteria based on other SDB header variables (e.g. environmental parameters) may also be applied.

Next, the AU definition must be specified and applied to the spectra passing the initial data selection. Since the AU definition may restrict the types of background estimation models which can be applied, the background estimation model should be determined before specifying the AU definition. Both the AU definition and the spectra passing the initial data selection are input to an IGORE application which searches the spectra for valid AU's. The output of this application is an array of SDR's, one element for each valid AU, which contain pointers to the spectra making up each AU.

The SDR array containing the valid AU's is then input to an IGORE application which performs the background estimation and background subtraction. Background estimation and background subtraction is performed for each valid AU separately. The background estimation is assumed to be linear in the measured background spectra:

$$\tilde{B}(j) = \sum_{i=1}^{N_{spec}} A_i B_i(j) \qquad (1)$$

where N_{spec} is the number of background spectra in the AU, i is the background spec-

trum number and j is the spectrum channel number. The coefficients A_i are determined by unweighted polynomial interpolation over one or more selected parameters, assuming no energy dependence. The currently supported interpolation parameters are time and detector step angle (scan angle). Interpolation including other parameters (e.g. rigidity, time from last SAA passage, etc.) may also be supported, as required. The resulting background-subtracted spectrum and uncertainties are written to an output SDB file. One background-subtracted spectrum is written for each valid AU. Also written to this SDB file is a set of pointers to the spectra forming the AU, the AU definition used to identify those spectra, the estimated background spectrum and uncertainties, the A_i coefficients used to estimate the background spectrum, and a complete SDB header containing the environmental parameters for the difference spectrum.

After the background subtraction has been performed, improved sensitivities are achieved by summing the individual difference spectra. Secondary data selection criteria may be applied to the difference spectra prior to summing. Like the initial data selection, the secondary data selection is performed in IGORE using the IDL WHERE function. The selection is again generally performed on SDB header variables, but the criteria are typically constructed to remove systematics in the spectrum caused by variations in the background which may not have been accurately modeled in the background estimation process. Typical secondary data selection criteria might impose limits on environmental parameters such as rigidity, time from last SAA passage, Earth zenith angle, and anti-coincidence shield rates. Difference spectra passing the secondary data selection criteria are then summed separately for each detector. The propagation of the uncertainties in the summed spectra includes the covariance caused by the multiple use of some background spectra. The A_i coefficients are also summed for use in generating the instrument response matrix.

An important aspect of the spectral analysis process is the identification and minimization of residual systematic features in the summed difference spectra. Residual features will be generated if there are systematic errors in the background estimation model. Such residual systematics may be reduced either by identifying and removing from the summed difference spectra those data accumulated during periods when the systematics in the background estimation model occur, or by developing new background estimation models. The current data analysis has typically been performed using a simple linear background estimation model which interpolates in time between two background spectra and with no environmental data selection. For standard two-week OSSE observations this method appears to produce relatively clean spectra with few residual background line features, though background continuum residuals are seen at energies below ~ 2 MeV. Difference spectra produced over shorter periods (e.g. one-week intervals) appear to show stronger residual line features, suggesting that these background residuals may "average out" over a complete two-week observation during which many of the various orbital environmental conditions are sampled. Appropriate data selection on environmental parameters and/or more detailed background estimation models will likely reduce the residual line and continuum features significantly.

The summed difference spectra may then be fitted for spectral lines and/or continua. When fitting for the parameters of spectral lines alone, the summed difference spectra may be fitted directly. Fitting the spectrum for continua, however, requires spectral deconvolution. The only method of spectral deconvolution currently supported is forward-folding. Spectral deconvolution requires an instrument response matrix for each detector pointing position used in the AU. The instrument response matrices are generated from the results of Monte Carlo simulations of the OSSE detectors and the A_i coefficients associated with the summed difference spectrum. When using the forward-folding deconvolution method, a model for the incident photon spectrum is selected and folded through the instrument response matrices. The resulting model spectrum is then compared with the data and the model parameters modified to achieve the best fit. The resulting estimate of the incident photon spectrum is model dependent, however.

CONCLUSION

OSSE spectral analysis is complicated because of the typically low signal-to-noise ($\sim 0.1\%$) and the large background variability. The OSSE instrument was designed to address these difficulties by offset-pointing the detectors from the source to perform periodic background measurements. In order to analyze OSSE spectral data effectively and achieve the statistical sensitivity, it will be necessary to develop a detailed understanding of the background spectrum and its variations. IGORE, the OSSE spectral analysis system, has been designed to provide the ability to perform detailed studies of the background spectrum and to use the OSSE offset-pointed observations to perform spectral analysis of astrophysical sources. New analysis methods may also be incorporated into the IGORE system, as required.

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Figure Captions

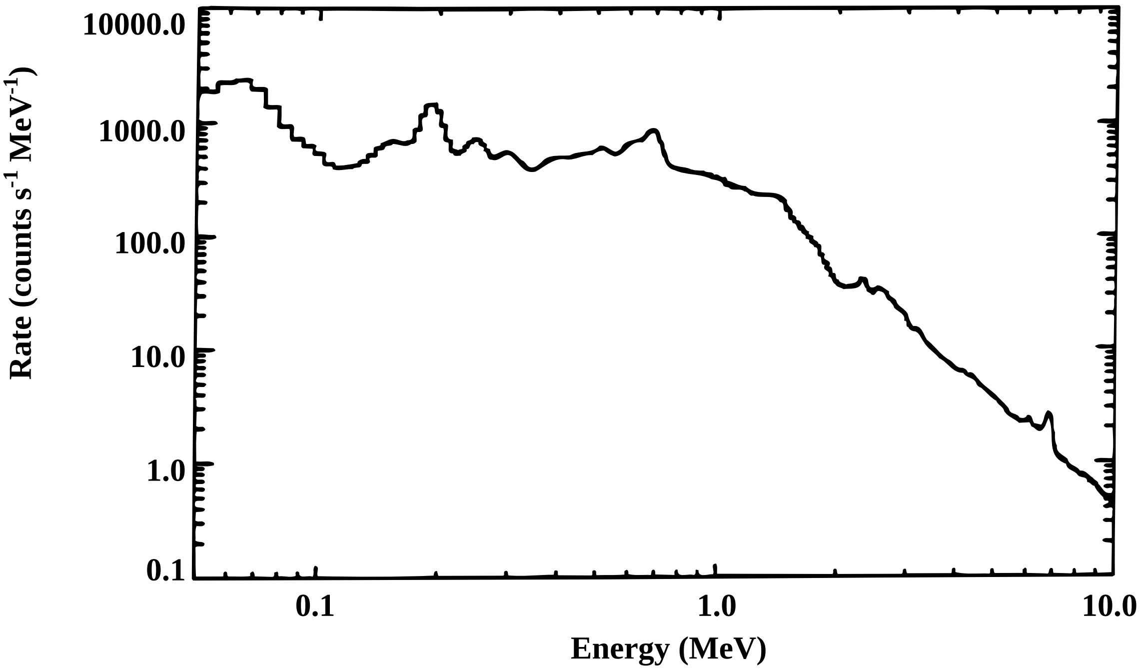
Figure 1. A typical OSSE background spectrum. The spectrum represents the average of all spectra accumulated on July 19, 1991 from a single detector. Both Low and Medium range spectral data are displayed, with overlap in the range 0.7- 1.5 MeV.

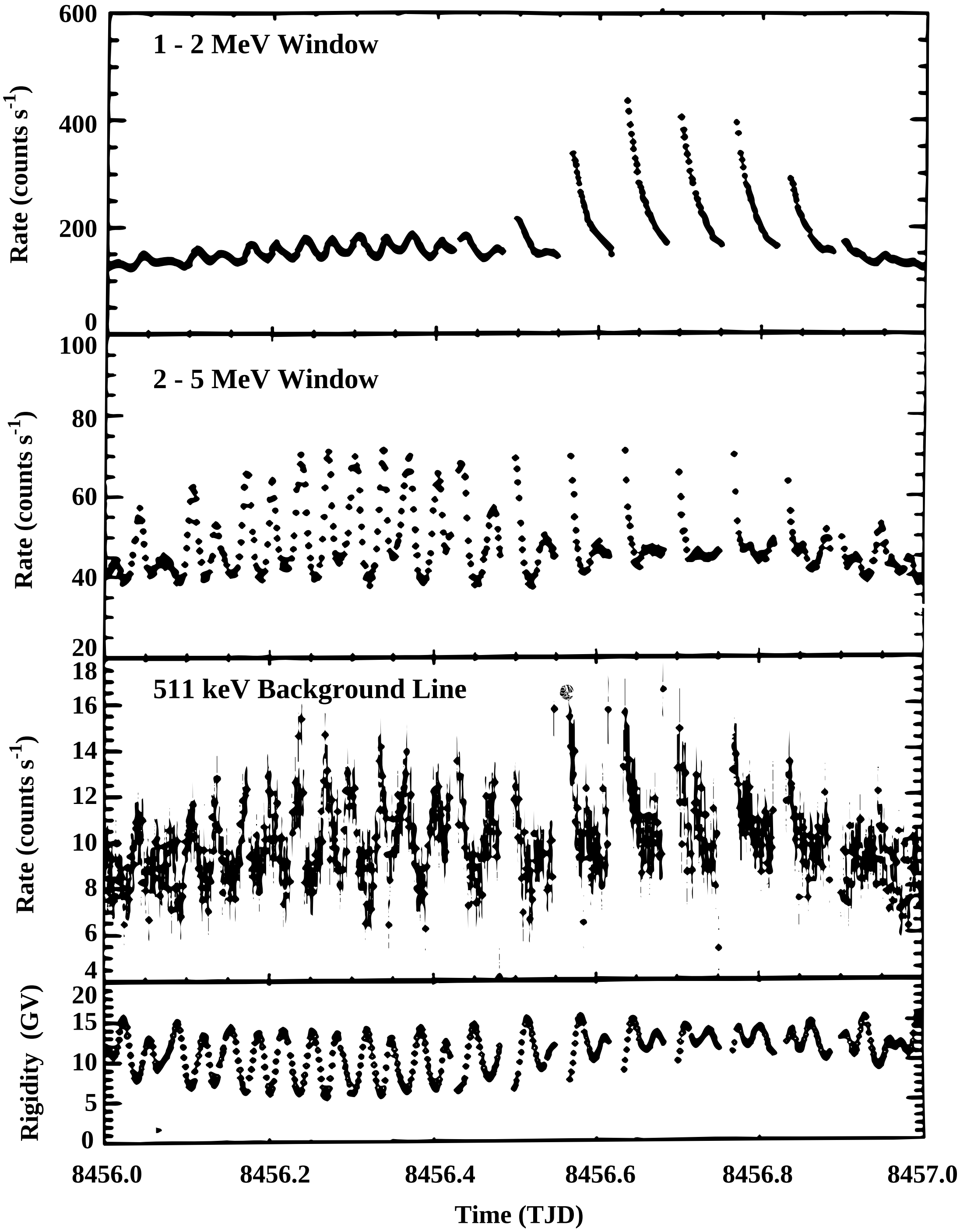
Figure 2. Observed temporal variations in background rates for two continuum windows and for the background 511 keV line. The data shown are from a single detector and were accumulated on July 19, 1991. Also shown is the variation of local vertical geomagnetic cutoff rigidity. Missing data correspond to periods during which the spacecraft was passing through the SAA.

Figure 3. An example of a simple OSSE pointing strategy. The rectangles (not drawn to scale) represent the OSSE field-of-view for the source and background accumulations. The instrument scan plane corresponds to the spacecraft X-Z plane. A possible observation sequence for each detector is also given.

Figure 4. An example of a more complex OSSE pointing strategy. The rectangles (not drawn to scale) represent the OSSE field-of-view for the source and background accumulations. The instrument scan plane corresponds to the spacecraft X-Z plane. A possible observation sequence for each detector is also given.

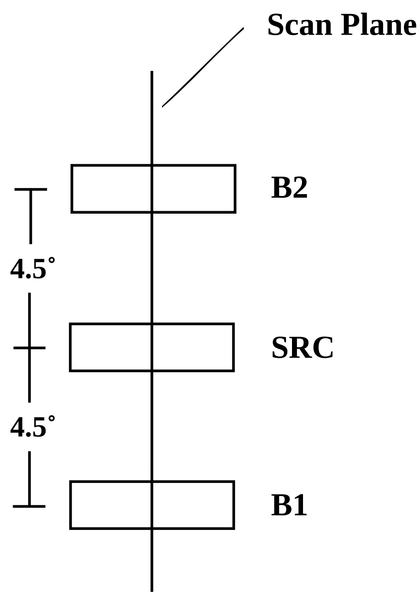
Figure 5. An outline of the major steps required to perform OSSE spectral analysis.


10000.0
1000.0
100.0
10.0
1.0
0.1
Rate (counts s^{-1} MeV^{-1})
0.1
1.0
10.0
Energy (MeV)
Figure 1



1 - 2 MeV Window
Rate (counts s-1)
600
400
200
0
2 - 5 MeV Window
Rate (counts s-1)
100
80
60
40
20
511 keV Background Line
Rate (counts s-1)
18
16
14
12
10
8
6
4
Rigidity (GV)
20
15
10
5
0
8456.0
8456.2
8456.4
8456.6
8456.8
8457.0
Time (TJD)

Figure 2



Observation Sequence

Det #1	Det #2	Det #3	Det #4
B1	B2	SRC	SRC
SRC	SRC	B2	B1
B2	B1	SRC	SRC
SRC	SRC	B1	B2

Figure 3

Observation Sequence

Det #1	Det #2	Det #3	Det #4
B1	B2	S_{+1}	S_0
S_0	S_{-1}	B2	B1
B2	B1	S_0	S_{-2}
S_{+2}	S_0	B1	B2

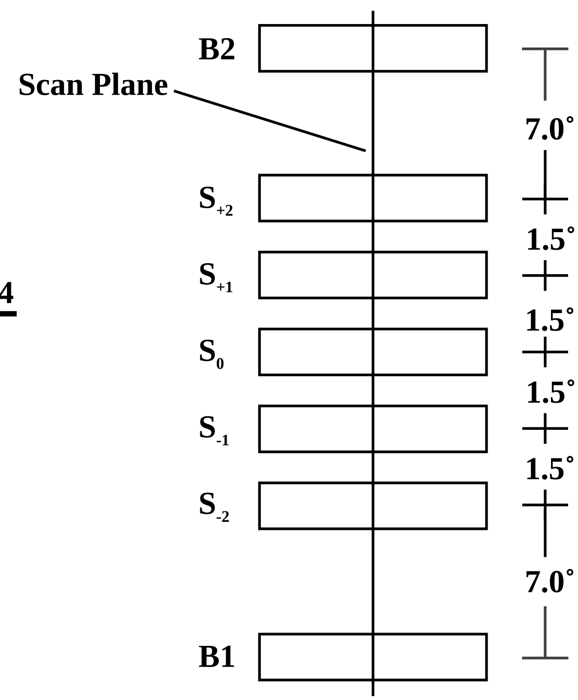


Figure 4

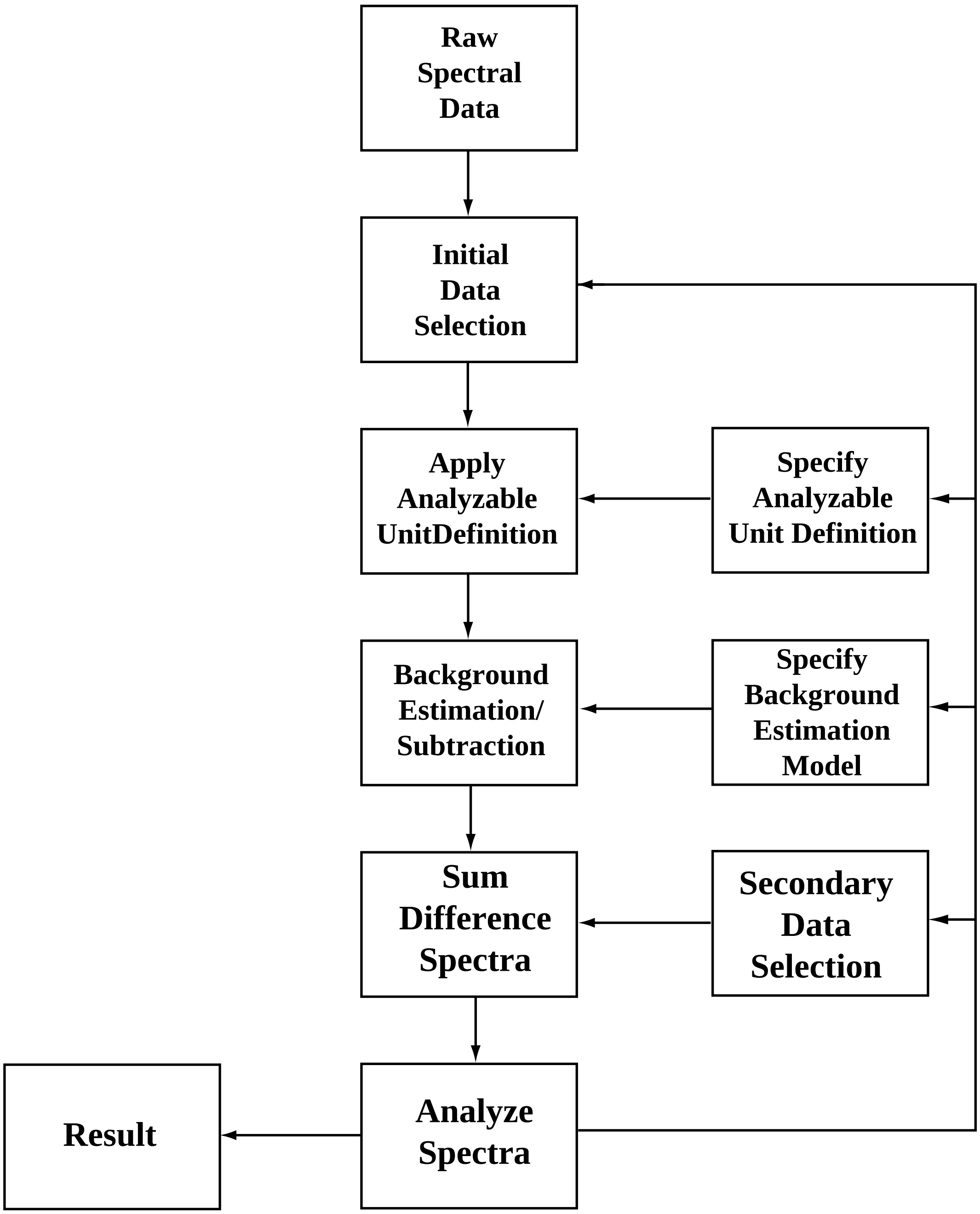

Raw Spectral Data
Initial Data Selection/
Apply Analyzable UnitDefinition
Specify Analyzable Unit Definition
Background Estimation/ Subtraction
Specify Background Estimation Model
Sum Difference Spectra
Secondary Data Selection
Result
Analyze Spectra

Figure 5